1. Science aim/goal:

To quantify the dust enrichment history of the Universe, uncover its composition and physical conditions, reveal the first cosmic sources of dust, and probe the properties of the earliest star formation.

2. Overview:

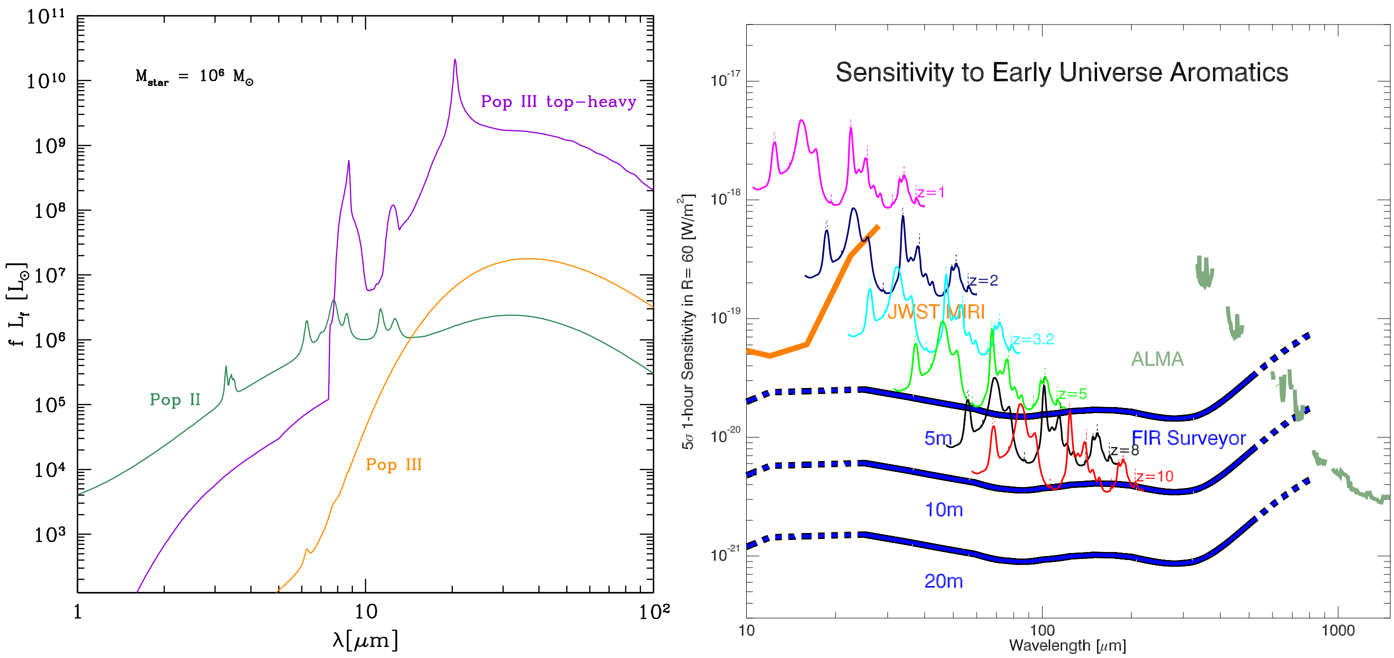
Scientific Importance: Astrophysical dust comprises less than one-hundredth of one percent of the baryonic mass of the Universe, yet approximately one-half of all energy radiated by stars and accreting black holes over its history has been reprocessed by dust to long wavelengths. Dust shrouds the most intense regions of black hole accretion and star formation, and, as it is comprised of condensable species like C, Si, Fe, and O, is a sensitive tracer of the abundance of heavy elements. Yet the origin of the large dust reservoirs ($\sim 10^8 M_\odot$) now being found in galaxies and quasar hosts at z=5–7.5, only *several hundred Myr after star formation commences*, is unknown, with possible explanations ranging from ultra-high mass supernovae, rapid ISM growth, or fast-evolving massive AGB stars. Studying the broad spectral dust features in the mid-infrared (3–30μm) from a widely drawn sample of early galaxies is the only way to provide critical and unique information on dust origin, composition, and properties like grain size distribution, as well as to track the underlying gas metal content (using e.g. the fractional power of PAH emission). Indeed, due to the very different expected dust compositions and mass yields of low metallicity PopII and PopIII stars, *dust signatures can directly probe the properties of the earliest phases of star formation* (see Fig. 1a).

Measurements Required: Individual dust emission bands like PAHs contain *up to 5% of the bolometric luminosity* of galaxies, about 10 times more than even the brightest gas emission lines like [CII]. Deep spectroscopy at rest frame 3–30μm of several hundred redshift-selected sources with luminosities $10^{11\text{-}13} L_\odot$ will enable us to track the onset of dust production and explore its progenitors. Blind spectral surveys centered on the brightest dust emission features (e.g. PAHs at 7.7 and 11.3μm) will also provide large samples with well-measured, independent redshifts, even for strongly UV/optical-obscured galaxies. Since bulk dust features are broad ($\lambda/\Delta\lambda \sim 5$), the required spectral resolution is only R=50–100, resulting in exceptional background-limited sensitivity (see Fig. 1b).

Uniqueness to 10 micron to few mm wavelength facility: At z>5, only a sensitive far-IR platform can provide access to the rest-frame MIR emission of galaxies, which is crucial for assessing the content and conditions of the dusty ISM at the earliest star-forming epochs. These wavelengths are nearly entirely obscured by the atmosphere. Additionally, since the CMB temperature increases linearly with redshift, above z~5, the dust temperatures of many galaxies will approach $T_{\rm CMB}$, rendering differential detection in the RJ tail of their dust SEDs increasingly difficult. With high intrinsic luminosities and direct or stochastically-heated temperatures of hundreds of Kelvin, the dust features emitting in the rest frame MIR (PAHs, Silicates) can be readily observed above this warm CMB background. Rest-frame UV absorption studies against in situ gamma-ray bursts or background quasars will provide some complementary information (e.g. on the slope and UV absorption features of the dust extinction curve at these epochs), but such methods do not sample the full range of galaxy properties or help constrain dust mass, nor are they diagnostic of the properties of the underlying star formation.

Longevity/Durability: At these redshifts, ground facilities like ALMA can measure critical cooling lines like [CII] (a dominant coolant of neutral gas in most galaxies), which, together with PAH power, can reveal how radiative energy flows through the ISM of the first galaxies, setting the gas temperature and controlling the efficiency of star formation. At these epochs, JWST will provide some coverage of the shortest wavelength dust features (e.g. 3.3μm PAH), but these bands are substantially weaker, and arise only from the smallest dust grains, providing limited information on composition and conditions. Only a sensitive, large collecting area space facility in the 100μm range can fully unveil the first dust in the Universe.

3. Figure:



Left: Predicted rest-frame dust emission features for different modes of star formation in the early Universe (Schneider+ in prep). A time-averaged 10^6 M☉ burst is modeled (Pop II 0.1–100M☉, 0.01 Z☉, 40Myr avg.; Pop III 0.1–100M☉, 0.0 Z☉, 40Myr avg.; Pop III Heavy 50–500M☉, 0.0 Z☉, 4Myr avg.). The strong SiO_2 bands produced by massive pair-instability SNe (violet curve) are a tell-tale signature of a high dust-yield, top-heavy IMF, whereas PAH features likely indicate some small initial metallicity $Z \gtrsim 0.01$. **Right**: The predicted sensitivity of a filled-aperture background-limited telescope at (binned) spectroscopic resolution R=60, demonstrating the detection capability for a redshifted PAH template of a normal 10^{12} L☉ star-forming galaxy at z=5–10 (Bradford+ in prep). JWST/MIRI and ALMA Band 7–10 wavelength coverage and sensitivities are also shown for comparison.

4. Performance Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	μm	20–220	20–300	Note a
Number of targets	#	100	1000	
Survey area	deg.^{2}	3	6	Note b
Angular resolution	arcsec	5	2	
Spectral resolution	**λ/Δλ**	>50	>150	Note c
Spectral line sensitivity	W m^{-2}	10^{-20}	2×10^{-21}	5σ, 1hr, at (binned) resolution
Signal-to-noise		5	15	
Dynamic range		10:1	25:1	For crystallinity, band/continuum variations

a. Probing the 3–25μm rest frame dust features at z=6–10.
b. At z>5, Bethermin+ 2012 predict ~100 ULIRGs and ~1000 LIRGs per square degree, yielding thousands of PAH detections with the targeted sensitivity. Confusion is not a concern in the spectral direction for wavelengths below 100μm, and template-fitting can yield precise redshifts.
c. Features are intrinsically broad, but higher resolution is needed for sub-feature decomposition/crystallinity measurements.

5. Key references:

Bethermin+ 2012; *Carrilli & Walter, ARA&A 2013; Da Cunha+ ApJ 2013*